Equivalent-Circuit Transmission Line Model of a Ferrite-Filled Rectangular Waveguide Phase Shifter

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Increased levels of circuit integration offer undeniable benefits in terms of performance, size, and cost. Given this motivation, the move toward higher levels of on-chip integration has been relentless. However, significant technological obstacles must often be overcome to accommodate this trend. In many instances, some of the obstacles are deemed to be insurmountable, leading to the conclusion that certain circuit components are inherently incompatible with monolithic circuit integration and that these should remain off-chip instead. Chip-packaging materials have therefore been targeted as the next medium for integration. Multilayer low-temperature cofired ceramic (LTCC) has emerged as an attractive packaging system for sustaining further integration efforts. Not only can LTCC provide embedded resistive, capacitive, and inductive elements, but its low losses also make it conducive to distributed microwave circuitry. In addition, novel three-dimensional microwave components often result from the judicious use of the LTCC package's vertical dimension.

Recently, a fully-integrated, antisymmetrically-biased rectangular waveguide ferrite phase shifter was demonstrated for millimeter-wave applications (J.R. Bray & L. Roy, *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 1732–1739, July 2004). The phase shifter, including its magnetostatic bias lines, was fabricated entirely of LTCC ferrite tape layers and was completely buried within the LTCC stack, thereby demonstrating how a three-dimensional ferrite device could be fully integrated within an existing packaging system. The non-reciprocal behavior of the device was theoretically studied using an analytical field derivation in which the phase constant of the guide was obtained by solving a transcendental equation.

A transmission line model is a useful tool for portraying the behavior of this device because it avoids the more complicated electromagnetic field equations. To this end, this paper investigates a lumped-element distributed circuit model for the ferrite-filled rectangular waveguide phase shifter, in which the non-reciprocal nature of the device is modeled using a gyrator circuit element. The model is based on the configuration that was first proposed by Boyd (C.R. Boyd, Jr., *Proc. SBMO International Microwave Symp., Brazil*, pp. 209–216, July 1985), although at that time, the full field equations for the ferrite-filled phase shifter were not available and the model's validity could not be confirmed. With the availability of the field expressions, the impedance, power, and stored electric and magnetic energy relations may now be fully explored, allowing the model's range of validity to be assessed. The model, though never exact, is shown to be a useful tool for quickly assessing the behavior of the ferrite-filled phase shifter.